

Radio-mode feedback in local AGNs: dependence on the central black hole parameters

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ABSTRACT

Radio-mode feedback, in which most of the energy of an active galactic nucleus is released in a kinetic form via radio-emitting jets, is thought to play an important role in the maintenance of massive galaxies in the present-day Universe. We study the link between radio emission and the properties of the central black hole in a large sample of local radio galaxies drawn from the Sloan Digital Sky Survey, based on the catalogue of Best & Heckman (2012). Our sample is mainly dominated by massive black holes (mostly in the range 10^8 – $10^9 M_\odot$) accreting at very low Eddington ratios (typically $\lambda < 0.01$). In broad agreement with previously reported trends, we find that radio galaxies are preferentially associated with the more massive black holes, and that the radio-loudness parameter seems to increase with decreasing Eddington ratio. We compare our results with previous studies in the literature, noting potential biases. The majority of the local radio galaxies in our sample are currently in a radiatively inefficient accretion regime, where kinetic feedback dominates over radiative feedback. We discuss possible physical interpretations of the observed trends in the context of a two-stage feedback process involving a transition in the underlying accretion modes.

Key words: black hole physics – galaxies: active – radio continuum: galaxies.

1 INTRODUCTION

Accreting black holes at the centre of galaxies release huge amounts of energy into the surroundings in both radiative and kinetic forms. The interaction between this ‘feedback’ and the ambient material can have a strong impact on the host galaxy, and active galactic nucleus (AGN) feedback is now thought to play a major role in galaxy evolution. Observations show a number of important correlations between the central black hole and its host galaxy, such as the black hole mass–velocity dispersion relation (the so-called M – σ relation) and the black hole mass–bulge stellar mass relation (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Marconi & Hunt 2003; Häring & Rix 2004). The existence of such tight correlations indicates a close coupling between the central black hole and its host galaxy, suggesting some form of ‘co-evolution’. The observed correlations are generally interpreted in the framework of AGN feedback models (Silk & Rees 1998; Fabian 1999, King 2003; Murray, Quataert & Thompson 2005; Fabian 2012, and references therein). Two main modes of feedback are observed in nature: the radiative (or quasar) mode and the kinetic (or radio) mode, which possibly operate at different stages in the evolution of galaxies (Fabian 2012).

AGN feedback is usually invoked to suppress star formation in the host galaxy, either by removing or heating the ambient gas in the radiative and kinetic modes, respectively. The quasar mode is associated with radiatively efficient accretion approaching the Eddington limit, and is most active at high redshifts ($z \sim 2$), close to the peak epoch of AGN activity. In contrast, in the radio mode, much of the energy output is in kinetic form and channelled through relativistic radio jets. The kinetic mode is generally associated with lower accretion rates and mainly operates at lower redshifts. The mechanical energy deposited by the jet can heat the ambient gas and prevent radiative cooling, thus inhibiting star formation, and limiting the stellar mass of the host galaxy. The required balance between heating and cooling rates seems to be preserved in this maintenance mode, which shapes the late evolution of massive galaxies. In the present-day Universe, radio-mode feedback typically operates in massive galaxies with low accretion rates, and is commonly observed in local giant ellipticals.

The relative importance of radio emission, compared to the other wavebands, can vary significantly in different sources. Accordingly, AGNs can be divided into two distinct classes: radio-loud (RL) and radio-quiet (RQ), leading to the well-known RL/RQ dichotomy. The distinction between the two classes is based on the radio loudness of the source, usually quantified by the radio-loudness parameter $R = \frac{F_r}{F_o}$, defined as the ratio of monochromatic luminosities at 5 GHz and optical B band at 4400 Å (Kellermann et al. 1989). The

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formal boundary between the RL and RQ objects is set at $R \sim 10$ (Kellermann et al. 1994). A bimodal distribution, formed by two distinct sequences, can be seen in the radio luminosity versus optical luminosity plane (e.g. Xu, Livio & Baum 1999; Sikora, Stawarz & Lasota 2007), although the existence of a real physical dichotomy in the radio-loudness distribution of AGNs has been questioned (Falcke, Sherwood & Patnaik 1996; Lacy et al. 2001; Baloković et al. 2012, and references therein).

The relation between radio emission and the properties of the central accreting black hole, i.e. black hole mass and accretion rate, has been extensively studied in the literature for a variety of AGN samples selected following different selection criteria (Laor 2000; Ho 2002; McLure & Jarvis 2004; Sikora et al. 2007; Chiaberge & Marconi 2011; Sikora et al. 2013; Wu et al. 2013). Two interesting trends seem to emerge by analysing the dependence of the radio loudness on the central black hole parameters: an anticorrelation with the Eddington ratio ($\lambda = L_{\text{bol}}/L_{\text{Edd}}$), and a possible correlation with the black hole mass (M_{BH}). In particular, Sikora et al. (2007) report a double-sequence structure in the radio luminosity versus optical luminosity plane, in which both the RL and RQ sequences are observed to follow the same trend of increasing radio loudness with decreasing Eddington ratio. Here, we re-visit the issue based on a large sample of local radio-AGN drawn from the Sloan Digital Sky Survey (SDSS), and examine the dependence of the radio emission on the properties of the central black hole, with the aim of better characterizing the occurrence of radio-mode feedback in the local Universe.

The paper is organized as follows. In Section 2, we introduce our sample of radio sources drawn from the SDSS, and describe the data analysis method in which we try to carefully take into account measurement uncertainties and error propagation. In Section 3, we present the dependence of the radio emission on black hole mass and Eddington ratio, and in Section 4, we compare our results with previous studies in the literature. We discuss a number of possible physical interpretations in Section 5.

2 SAMPLE AND DATA ANALYSIS

We have compiled a sample of RL AGNs derived from the catalogue provided by Best & Heckman (2012), which was constructed by cross-matching radio sources from the National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey (NVSS; Condon et al. 1998) and the Faint Images of the Radio Sky at Twenty centimetres (FIRST; Becker, White & Helfand 1995) survey with objects in the 7th data release (DR 7) of the SDSS (Abazajian et al. 2009). The original Best & Heckman (2012) catalogue includes 18 286 sources. We use stellar velocity dispersion measurements and [O III] luminosities to derive black hole properties, and we therefore also only use objects with $\sigma < 400 \text{ km s}^{-1}$ and require that the uncertainties on σ and $L_{\text{O III}}$ must be less than 10 and 20 per cent, respectively; our final sample has 1091 objects.

We use the SDSS data base and the FIRST/NVSS surveys to derive three measurements for each AGN: the [O III] luminosity, the stellar velocity dispersion, and the radio flux at 1.4 GHz, all with related uncertainties. We then apply a number of transformations to the data in order to derive quantities related to the central black hole.

2.1 Radio luminosity

The radio luminosity is computed using the standard luminosity–flux relation, with the radio flux measured at 1.4 GHz. The radio-

loudness parameter used in the literature is based on the radio luminosity at 5 GHz and the B -band luminosity at 4400 Å, defined as $R \sim 10^5 (L_{5 \text{ GHz}}/L_B)$ (Sikora et al. 2007), where the nuclear B -band luminosity is assumed to be a tracer of the accretion luminosity (see Section 2.2). The conversion from 1.4 to 5 GHz luminosity is computed by assuming a radio spectral index of 0.9 ± 0.35 obtained from a Gaussian fit to the data provided by Randall et al. (2012).

2.2 Optical luminosity

We do not have a direct measure of the B -band luminosity due to the presence of the AGN host galaxy, so in order to allow for comparisons with previous studies, we also need to derive a relationship between the [O III] luminosity and the B -band luminosity. Shen et al. (2011) report a correlation between the [O III] line luminosity and the continuum luminosity at 5100 Å for a sample of 105 783 quasars in the SDSS (DR 7) quasar catalogue. The best-fitting relation is given by $\log(L(5100/\text{erg s}^{-1})) = (0.771 \pm 0.002) \log(L([\text{O III}]) \text{ erg s}^{-1}) + (12.13 \pm 0.08)$. The 5100 Å luminosity is then converted into the 4400 Å B -band luminosity by assuming an optical spectral index of $\alpha_0 = 0.5$. However, this relationship includes a large amount of scatter and also may introduce systematics since it is defined for quasars while our sample does not include any bright quasars and the continuum can be dominated by stellar light. Moreover, the power-law index of $\alpha_0 \sim 0.5$ at optical–UV wavelengths is a typical value obtained for luminous AGNs (e.g. Vanden Berk et al. 2001), while there are indications that the spectral slope might be steeper in lower luminosity sources (Ho 2008, and references therein). In fact, a characteristic feature of the spectral energy distribution of low-luminosity AGNs is the lack of the big blue bump component, with a steep optical–UV slope, although dust reddening effects have been invoked (Maoz 2007).

On the other hand, the [O III] line luminosity is often used as a direct tracer of the AGN bolometric luminosity (e.g. Heckman et al. 2004). The [O III] emission line is produced by photoionization of gas in the narrow-line region, and is thus less affected by dust extinction due to the obscuring torus. But the optical line is also subject to extinction due to dust present in the interstellar medium of the host galaxy, and corrections for this effect should be taken into account (Kauffmann & Heckman 2009). In addition, while the [O III] luminosity is widely used as a proxy of the bolometric luminosity of radiative-mode AGN, it is not clear that it is a good indicator in the case of lower luminosity objects dominated by the kinetic output. One should therefore keep in mind these caveats when interpreting the results.

2.3 Black hole mass

We derive the black hole mass from the stellar velocity dispersion by using the $M-\sigma$ relation determined by McConnell & Ma (2013):

$$\log M_{\text{BH}} = (8.32 \pm 0.05) + (5.58 \pm 0.34) \log(\sigma) + (0.42 \pm 0.04),$$

where σ is in units of 200 km s^{-1} . The Eddington ratio is given by

$$\lambda = L_{\text{bol}}/L_{\text{Edd}},$$

where $L_{\text{bol}} = 10L_B$ (Richards et al. 2006). In Section 3, we also estimate the bolometric luminosity directly from the [O III] emission line, $L_{\text{bol}} = 3500L_{[\text{O III}]}$ (Heckman et al. 2004).

2.4 Fitting procedure

In practice, the propagation of the measurement uncertainties when performing these transformations can be non-trivial, in part because the transformations themselves can have uncertainties, e.g. in the $M-\sigma$ relation. We therefore use a Monte Carlo method to robustly propagate all of the known uncertainties by drawing 10 000 samples from the measured distribution for σ , $L_{\text{[O III]}}$, and $F_{1.4\text{ GHz}}$ for each AGN. We then transform these samples into M_{BH} , λ , and R using the above relations, including drawing samples for uncertain parameters as in the $M-\sigma$ relation, and find the mean and standard deviation of the transformed samples; we then take these to be our ‘measurements’ for each of the derived quantities. Note that this method also allows us to determine the covariance between all of the quantities, both measured and derived.

The purpose of this work is to look at the relationship between the radio luminosity and black hole properties of a large sample of RL AGNs. We quantify these relationships by performing linear fits of one parameter against another, following the formalism of Kelly (2007). In particular, this allows us to robustly include the uncertainties and correlations within the data set, and we are also able to quantify the intrinsic scatter in the linear fits (i.e. an estimate of the true physical scatter deconvolved from the significant scatter induced by measurement uncertainties). It is important to note that attempting to determine the selection function for our data set is intractable, but understanding selection biases is critical for interpreting the linear relationships that we are fitting. This problem is slightly alleviated by employing the Kelly (2007) scheme, which empirically determines the actual distributions from which our samples are drawn, although this is the product of the true distribution and the selection function.

In the following, we split our radio-AGN sample into two subclasses, high-excitation and low-excitation radio galaxies (HERG and LERG), according to the classification introduced by Best & Heckman (2012). The resulting sample is composed of 890 LERGs and 179 HERGs.

3 RESULTS

3.1 Dependence on the black hole mass

In Figs 1 and 2, we plot the 5 GHz radio luminosity ($L_{5\text{ GHz}}$) and the radio-loudness parameter (R) as a function of the black hole mass (M_{BH}), respectively. The majority of the objects are RL according to the standard RL/RQ division based on the radio-loudness parameter ($\log R = 1$) and the alternative division based on the absolute radio luminosity (e.g. Best et al. 2005, $L \sim 10^{23} \text{ W Hz}^{-1}$ at 1.4 GHz corresponding to $L \sim 5 \times 10^{38} \text{ erg s}^{-1}$ at 5 GHz). The possible existence of a black hole mass threshold dividing RL and RQ AGNs has been suggested in the literature, with a somewhat arbitrary limit set around $\sim 10^8 M_{\odot}$ (Laor 2000; McLure & Jarvis 2004; Chiaberge & Marconi 2011). We observe that most of the radio galaxies in Figs 1 and 2 have large black hole masses ($M_{\text{BH}} \gtrsim 10^8 M_{\odot}$). Although RL objects seem to be typically associated with more massive black holes, the previously reported detection of a sharp boundary at $M_{\text{BH}} \sim 10^8 M_{\odot}$ is not evident in our sample. The fact that the majority of our sample is RL and skewed towards large black hole masses is partly due to our sample definition based on radio selection. In fact, sample selections based on strong radio emission tend to yield the most massive black holes, and presumably the most massive host galaxies (Best et al. 2005), a trend that has also been noted in McLure & Jarvis (2004). As previously observed

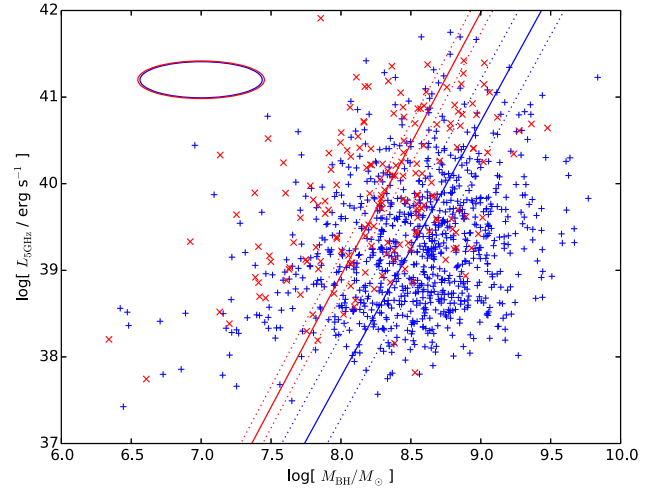


Figure 1. The relationship between the 5 GHz radio luminosity and the black hole mass, with red crosses indicating HERGs and blue plus symbols indicating LERGs. The red solid line is our best-fitting linear relation for HERGs, $\log L_R = (38.9 \pm 0.2) + (3.0 \pm 0.6) [\log M_{\text{BH}} + 8]$, and the red dotted lines indicate the intrinsic scatter, which we find to be 0.24 ± 0.15 . The blue solid line is the best-fitting linear relation for LERGs, $\log L_R = (37.8 \pm 0.5) + (2.9 \pm 1.0) [\log M_{\text{BH}} + 8]$, with the blue dotted lines indicating an intrinsic scatter of 0.48 ± 0.12 . The ellipses in the upper-left corner illustrate the typical uncertainty and covariance for each AGN.

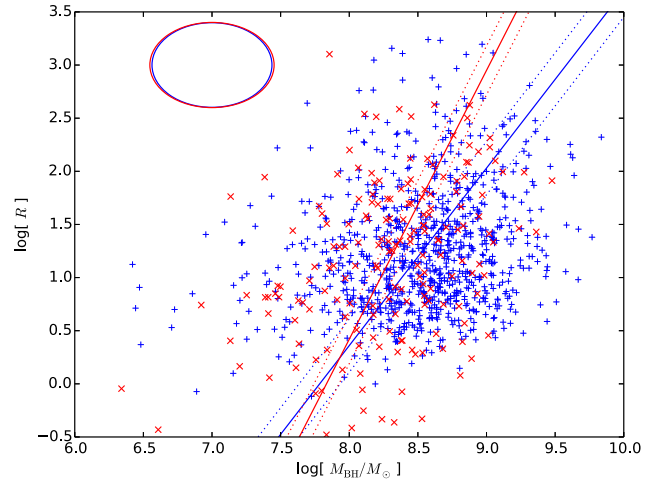


Figure 2. The same as Fig. 1, but now showing the radio loudness R versus the black hole mass for HERGs (red crosses) and LERGs (blue pluses). The best-fitting relation is $\log R = (0.4 \pm 0.2) + (2.5 \pm 0.7) [\log M_{\text{BH}} + 8]$ with 0.23 ± 0.14 dex intrinsic scatter for HERGs, and $\log R = (0.4 \pm 0.3) + (1.7 \pm 0.5) [\log M_{\text{BH}} + 8]$ with 0.25 ± 0.08 dex intrinsic scatter for LERGs.

by Best & Heckman (2012), HERGs typically tend to have lower black hole masses compared to the LERG population.

3.2 Dependence on the Eddington ratio

The radio-loudness parameter (R) as a function of the Eddington ratio (λ) is shown in Fig. 3. A strong trend of increasing radio loudness with decreasing Eddington ratio has been reported in many previous works (e.g. Ho 2002; Sikora et al. 2007, 2013). As already mentioned in Section 2, the way in which the B -band luminosities are derived here is not particularly reliable and introduces large uncertainties. It is therefore more relevant to define equivalent physical

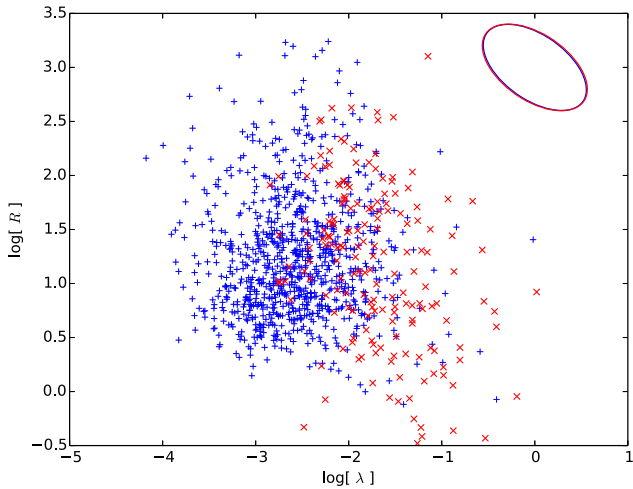


Figure 3. The radio loudness R versus Eddington ratio defined as $\lambda = 10L_B/L_{\text{Edd}}$, with HERGs indicated as red crosses and LERGs as blue pluses. We have not fitted a linear relation to these data because our derived L_B is likely to be affected by significant systematics, as discussed in the text. Note that there is also significant covariance between λ and R , as both quantities depend on L_B and the statistical uncertainty on L_B tends to be very large.

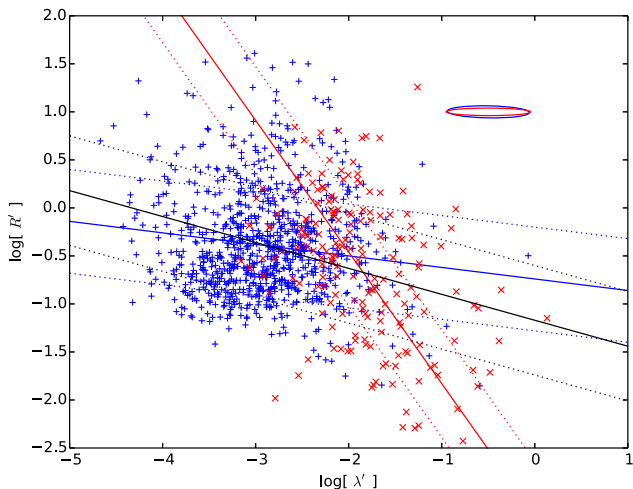


Figure 4. The same as Fig. 3, but now showing the radio loudness defined as $R' = L(1.4 \text{ GHz})/L([\text{O III}])$ versus the Eddington ratio defined as $\lambda' = 3500L([\text{O III}])/L_{\text{Edd}}$. The best-fitting relation is $\log R' = (-0.5 \pm 0.08) + (-1.4 \pm 0.4) [\log \lambda' + 2]$ with 0.56 ± 0.08 dex intrinsic scatter for HERGs, and $\log R' = (-0.5 \pm 0.07) + (-0.1 \pm 0.07) [\log \lambda' + 2]$ with 0.54 ± 0.01 dex intrinsic scatter for LERGs. The black line gives the best-fitting linear relation for the total population, $\log R' = (-0.3 \pm 0.04) + (-0.6 \pm 0.04) [\log \lambda' + 2]$, with 0.57 ± 0.01 dex intrinsic scatter.

quantities in terms of parameters closer to direct observables, i.e. avoiding spurious conversions as far as possible. We thus introduce an alternative measure for the radio-loudness parameter as the ratio of the 1.4 GHz radio luminosity to the [O III] line luminosity ($R' = L(1.4 \text{ GHz})/L([\text{O III}])$), and the Eddington ratio defined as $\lambda' = L_{\text{bol}}/L_{\text{Edd}}$, with the bolometric luminosity directly estimated from the [O III] line luminosity, $L_{\text{bol}} = 3500L([\text{O III}])$ (Heckman et al. 2004). In Fig. 4, we plot the radio-loudness parameter (R') as a function of the Eddington accretion rate (λ'), based on the new defined quantities. This plot is analogous to Fig. 3, and in particular

it is directly comparable to corresponding plots presented in Sikora et al. (2013). We observe that the radio-AGN sample is dominated by sources with low Eddington ratios, mainly $\log \lambda' < -2$, with a clear lack of sources approaching the Eddington limit ($\log \lambda' \sim 0$). The prevalence of low-accretion-rate objects already suggests that the local radio-AGNs are likely powered by some form of radiatively inefficient accretion flow (RIAF). In fact, the majority of the radio galaxies in our sample are classified as LERGs. We also observe that LERGs typically have lower Eddington ratios compared to HERGs; this important difference in the Eddington-scaled accretion rate is one of the main drivers that have led to the picture of the dichotomy in the present-day AGN population (Best & Heckman 2012).

From Fig. 4, we see that the density of points rises sharply below some critical value of the accretion rate, $\lambda' \sim 0.01$. A trend of increasing radio loudness with decreasing Eddington ratio, compatible with the R – λ anticorrelation reported in previous studies, can also be recovered in Fig. 4. But the lack of sources in the low-Eddington-ratio and low-radio-loudness regime could also be due to radio faintness related to flux limits, and the observed correlations may in part be driven by observational selection effects. We note that distinct slopes of the linear fits are obtained for the two populations, with HERGs having a steeper dependence on λ' than LERGs. Our best-fitting linear relation to the total population of local radio galaxies, taking into account all uncertainties, covariances, and intrinsic scatter, yields $R' \propto (\lambda')^{-0.3 \pm 0.04}$. This can be compared with the slope of ~ -0.5 found for a sample of galactic nuclei covering a wide range of nuclear luminosities (Ho 2002).

4 COMPARISON TO PREVIOUS WORK

The connection between radio emission and black hole parameters, i.e. black hole mass and accretion rate, has been investigated in many previous works. The correlation observed between jet and accretion powers, as traced by radio and emission-line/mid-infrared luminosities, suggests a close coupling hinting at some common physical mechanism (e.g. Fernandes et al. 2011, and references therein). But somewhat contrasting results have been reported in the literature (Xu et al. 1999; Laor 2000; Ho 2002; McLure & Jarvis 2004; Sikora et al. 2007; Chiaberge & Marconi 2011; Sikora et al. 2013).

A positive correlation between radio emission and black hole mass, whereby RL objects are associated with massive black holes, has been reported by several authors (Laor 2000; McLure & Jarvis 2004; Chiaberge & Marconi 2011). Based on a sample of 87 low-redshift ($z < 0.5$) Palomar-Green quasars, Laor (2000) claims a radio-loudness bimodality directly linked to the black hole mass: most of the quasars with $M_{\text{BH}} > 10^9 M_{\odot}$ are RL, whereas the majority of quasars with $M_{\text{BH}} < 3 \times 10^8 M_{\odot}$ are RQ. The correlation between radio emission and black hole mass has been confirmed in a much larger sample of optically selected quasars from the SDSS (McLure & Jarvis 2004). A significant correlation between absolute radio luminosity and black hole mass has also been claimed for this sample. The mean black hole mass of RL quasars is found to be larger than that of the RQ counterparts, with most of the RL objects having $M_{\text{BH}} \geq 10^8 M_{\odot}$. Indeed, the fraction of RL quasars with $M_{\text{BH}} \leq 10^8 M_{\odot}$ only forms a small minority of the luminous SDSS quasar population. The fraction of RL objects with $M_{\text{BH}} \leq 10^8 M_{\odot}$ is also a minority in our local radio-AGN sample, although the nature of the underlying accretion flows is expected to be quite different in the two populations. More recently, Chiaberge & Marconi (2011) investigate the relation between radio loudness and black

hole mass, using up-to-date mass estimates, which explicitly take into account the effects of radiation pressure. From the analysis of three selected samples, consisting of low-luminosity AGNs, quasi-stellar objects (QSOs), and SDSS AGNs, they conclude that there are basically no RL AGNs with $M_{\text{BH}} < 10^8 M_{\odot}$. The above studies suggest that a large black hole mass is a required element in order to produce a powerful radio source.

On the other hand, several studies report a significant anticorrelation between radio loudness and Eddington ratio (e.g. Ho 2002; Sikora et al. 2007, 2013), compatible with the trends observed for our local radio-AGN sample. A strong anticorrelation of the radio loudness with the Eddington ratio, and hence accretion rate, has been found for a sample covering a large range of luminosities from inactive nuclei up to luminous quasars (Ho 2002). The radio loudness is found to systematically increase with decreasing Eddington ratio, such that weakly accreting objects always tend to be RL, while most of the high-accretion-rate objects are RQ. This is also observed in the local radio-AGN sample, where most of the objects have low Eddington ratios and tend to be RL. Sikora et al. (2007) analyse a heterogeneous sample covering several orders of magnitude in both radio and optical luminosities, and observe that AGNs form two distinct sequences in the $L_{5\text{GHz}}-L_B$ plane separated by three orders of magnitude in radio luminosity. The trend of increasing radio loudness with decreasing Eddington ratio is followed separately by both sequences, with the same dependence. More recently, Sikora et al. (2013) report a strong anticorrelation between radio loudness and Eddington ratio for a sample of narrow-line radio galaxies at $z < 0.4$, confirming the negative trend found in earlier studies. Based on the observed systematic increase of the radio loudness with decreasing Eddington ratio, Sikora et al. (2007) propose a revised RL/RQ division depending on the accretion rate: $\log R = -\log \lambda + 1$ for $\log \lambda > -3$ and $\log R = 4$ for $\log \lambda < -3$. According to this new variable boundary criterion, essentially all of our sources would fall in the RQ category, suggesting that we are not actually sampling the most powerful radio sources.

The local radio-AGN sample analysed here is selected by cross-matching the SDSS with the NVSS/FIRST radio catalogues, resulting in a larger size sample compared to many previous works. The division into high-excitation and low-excitation sources is generally based on emission-line properties (Best & Heckman 2012, and references therein). For instance, an excitation index defined by a set of six emission lines has been used to split the 3CR radio galaxies sample into two distinct sub-populations (Buttiglione et al. 2010). Although such divisions are based on optical spectroscopic classification, high-excitation and low-excitation galaxies are also found to be distinct in terms of their ratio of emission line to radio luminosities. In fact, for a given radio luminosity, HERGs are observed to be brighter in the [O III] emission-line luminosity than LERGs by a factor of ~ 10 , implying differences in their radio-loudness characteristics.

Overall, the observed trends with black hole mass and accretion rate seem to be broadly consistent with results reported in previous studies. However, we note that the observational samples discussed in this section are selected according to different selection criteria (e.g. optically selected versus radio-selected) and are likely to be powered by different underlying accretion modes (see Discussion). For instance, the sample of optically selected quasars in the redshift range $0.1 < z < 2.1$, analysed by McLure & Jarvis (2004), is mainly composed of radiatively efficient sources accreting at considerable fractions of the Eddington rate. On the other hand, most of the radio galaxies observed in the local Universe emit relatively little

radiation, with much of the energy output released in kinetic form. Such sources are thus considered to be in the radiatively inefficient, jet-dominated regime (Best & Heckman 2012).

In addition, one may also need to include a note of caution. While we try to carefully take into account measurement uncertainties and error propagation, there are intrinsic issues related to the way in which different physical parameters are plotted. In particular, one is concerned with the $R-\lambda$ representation, in which the same physical quantity appears on both axis as ratioed quantities. The resulting biases might affect previously reported results, although this aspect has not been emphasized much in the literature. Furthermore, one should consider the orientation of the source with respect to the observer, with the associated beaming effect, leading to related issues on the use of the core or total radio luminosities (as discussed in e.g. Broderick & Fender 2011). With these caveats in mind, we attempt to provide possible physical interpretations of the observed trends in the next section.

5 DISCUSSION

We have analysed the dependence of the radio emission on black hole mass and Eddington ratio, based on a large sample of radio sources drawn from the SDSS. Most of the local radio-AGNs host massive black holes, typically in the mass range $M_{\text{BH}} \sim 10^8-10^9 M_{\odot}$. This suggests that radio galaxies are drawn from the population of massive galaxies, likely associated with giant elliptical galaxies in the local Universe. These giant ellipticals may be low-power radio sources, emitting relatively little radiation at optical wavelengths. We note that our radio selection preferentially selects the most massive black holes with low accretion rates, i.e. radiatively inefficient AGNs in the radio mode (Best & Heckman 2012).

In the R versus M_{BH} plot, we note a lack of objects with small black hole mass and high radio loudness for the radio-selected sample. Although RL AGNs are preferentially associated with massive black holes, for a given black hole mass, the range covered in both absolute radio luminosity and radio loudness can be several orders of magnitude. Moreover, one should take into account the large uncertainties in the black hole mass estimates, which tend to considerably broaden the observed distributions. It has been argued that a large black hole mass is a necessary condition in order to form a powerful radio source, although it is clearly not a sufficient one. In physical terms, it is not clear why the relative jet power of a source should have a strong dependence on the mass of the central black hole, and it is also not simple to imagine a physical process explicitly scaling with the black hole mass. One may consider downsizing effects, whereby in the present-day Universe low-mass black holes are in a radiatively efficient regime, accreting at rates close to the Eddington limit.

On the other hand, the dependence of the radio loudness on the accretion rate can be interpreted in terms of transitions in the underlying accretion flow modes. It is well known that at high Eddington ratios, accretion proceeds via a geometrically thin, optically thick accretion disc, with a high radiative efficiency. This is the standard radiatively efficient accretion mode (Shakura & Syun'yaev 1973). However, when the accretion rate drops below a certain critical value, the accretion flow can switch to a radiatively inefficient form (RIAF), such as the advection-dominated accretion flow (ADAF; Narayan & Yi 1994). An ADAF is generally characterized by a geometrically thick and optically thin accretion flow. Most of the energy released by viscous dissipation is retained in the gas and advected inwards, with the resulting radiative efficiency being very

low. In this radiatively inefficient regime, the bulk of the energy is emitted in kinetic form through radio jets, and the spectral energy distribution of ADAFs is generally expected to be RL with a lack of a strong blue bump component. The geometrical thickness of the inner torus, possibly surrounding a spinning black hole, may also help in the initial collimation of the radio jet (Rees et al. 1982; Fabian & Rees 1995). Therefore, the observed increase in the radio loudness with decreasing accretion rate can be understood in terms of two effects: an actual enhancement of the radio jet emission for low accretion rates and/or a decrease in the optical emission due to the decline of the radiative efficiency in the RIAF mode. Both effects may combine to produce the observed anticorrelation, as also noted by Wu et al. (2013).

A similar pattern is actually observed in the case of black hole binaries, in which the presence (or absence) of a radio jet is closely coupled with the accretion state (Remillard & McClintock 2006). The low-hard state, operating at low accretion rates, is usually associated with a steady radio jet; while in the high-soft state, corresponding to high accretion rates, the radio jet seems to be quenched. In black hole binaries, the state transitions and associated levels of radio jet emission are thus interpreted in terms of a change in the underlying accretion modes. In this framework, the RL AGNs in our local sample may be considered to reside in a state analogous to the low-hard state of black hole binaries.

The transition between the radiatively efficient accretion regime and the radiatively inefficient flow typically occurs around one percent of the Eddington rate ($\lambda \sim 0.01$), below which the kinetic output dominates over the radiative output (e.g. Churazov et al. 2005). Most of the objects in our radio-AGN sample have low Eddington ratios (typically $\lambda < 0.01$), and are likely to be powered by radiatively inefficient accretion, with most of the energy released in kinetic form. In this context, the ‘radio loudness’ of a source may be considered as a ratio of kinetic to radiative powers:

$$R \propto \frac{L_{\text{kin}}}{L_{\text{rad}}} \propto \frac{\lambda_{\text{kin}}}{\lambda_{\text{rad}}}, \quad (1)$$

where $\lambda_{\text{rad}} = \epsilon_{\text{rad}} \dot{M} c^2 / L_{\text{Edd}}$ and ϵ_{rad} is the radiative efficiency, which actually depends on the nature of the underlying accretion flow. In particular, below a certain critical accretion rate (\dot{m}_{crit}), the radiative efficiency scales as $\epsilon_{\text{rad}} \propto \dot{m} / \dot{m}_{\text{crit}}$, where $\dot{m} = \eta \dot{M} c^2 / L_{\text{Edd}}$ with η the accretion efficiency (Hopkins, Narayan & Hernquist 2006; Merloni & Heinz 2008). Assuming that the jet power scales linearly with the accretion rate ($\lambda_{\text{kin}} \propto \dot{m}$), and that the radiative output has a quadratic dependence on the accretion rate, of the form $\lambda_{\text{rad}} \propto \dot{m}^2$ (Mocz, Fabian & Blundell 2013), we obtain $R \propto \dot{m}^{-1}$. In a naive picture, this may explain the trend of the kinetic and radiative outputs with the accretion rate. It is interesting to note that, based on the so-called magnetically arrested accretion flow scenario, Sikora et al. (2013) predict a relation of the form $R \propto \lambda^{-0.4}$.

However, the accretion rate cannot be the only parameter determining the relative importance of the jet power in AGNs. In fact, for a given Eddington ratio, we observe a huge difference in radio loudness, e.g. a factor of $\sim 10^3$ between the RL and the RQ sequences (Sikora et al. 2007). Therefore, a further physical parameter is required, in addition to mass and accretion rate, and black hole spin has been suggested as a potential candidate. We recall that radio emission is implicitly coupled to the relativistic jet component, which is in turn coupled to the black hole spin; hence, a link between radio loudness and spin distributions has been searched for. This has led to the so-called spin paradigm, according to which the presence of a powerful jet, and associated radio emission, is determined by the

black hole spin (Blandford & Znajek 1977). The other important parameter is the strength of the magnetic flux threading the central black hole. It has been argued that the required magnetic flux accumulation can only occur in geometrically thick accretion flows, and in such a configuration one can obtain powerful jets (Sikora et al. 2013, and references therein). Therefore, the association of a high black hole spin and a geometrically thick flow can produce the most powerful radio sources (see also Meier 2001). Most likely, it is the combination of the three primary parameters, i.e. mass, accretion rate, and spin, that determines the radio loudness of a given source and its observational appearance. In addition, the underlying accretion flow geometry and the surrounding environment may also play an important role.

As already mentioned, the relative importance of radiative versus kinetic feedback modes seems to be regulated by the accretion state. At high accretion rates, close to the Eddington limit, the radiative efficiency is high and the radiative output dominates over the kinetic output (Churazov et al. 2005). However, at low accretion rates, the radiative efficiency drops dramatically, and the bulk of the energy is released in kinetic form via radio jets. The latter mode of feedback, characterized by low radiative efficiency, is thought to be the primary mode operating in the most massive galaxies in the present-day Universe. Indeed our sample of local radio-AGN is dominated by massive black holes accreting at very low fractions of the Eddington rate. This supports a picture in which local radio galaxies, powered by radiatively inefficient accretion, are currently in the regime of radio-mode feedback. We are clearly not sampling the most powerful radio sources, but rather the lower level radio AGN activity, which is more common and widespread in the local population. The transition between radiation-dominated and jet-dominated feedback modes has been discussed in terms of physical changes in the underlying accretion flows, from a radiatively efficient accretion disc to some form of radiatively inefficient flow. In an evolutionary scenario, a two-stage feedback process has been suggested, whereby the radiative mode dominates at high redshifts and builds the black hole–host galaxy relations, while at lower redshifts a stable state is maintained by the dominant kinetic mode (Churazov et al. 2005). The next step will be to explicitly study the relation between radio-mode feedback and the host galaxy properties, including stellar population parameters and environment.

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